Advanced-Gasification Combustion: Bench-Scale System Design and Experimental Results

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Abstract

Electricity produced from hydrogen in fuel cells can be highly efficient relative to competing technologies and has the potential to be virtually pollution free. Thus, fuel cells may become an ideal solution to many of this nation's energy needs if a satisfactory process is available for producing hydrogen from available energy resources such as coal, and low-cost alternative feedstocks such as biomass.

GE EER is developing an innovative fuel-flexible advanced gasification-combustion (AGC) technology for production of hydrogen for fuel cells or combustion turbines. The AGC module can be integrated into a number of Vision-21 power systems. It offers increased energy efficiency relative to conventional gasification and combustion systems and near-zero pollution. The development of the AGC technology is being conducted with U.S. DOE Vision-21 funding and is co-funded by GE EER, the California Energy Commission (CEC), and Southern Illinois University at Carbondale (SIU-C). The AGC technology converts coal and air into three separate streams of pure hydrogen, sequestration-ready CO_2, and high temperature/pressure oxygen-depleted air to produce electricity in a gas turbine.

This three-year program integrates lab-, bench- and pilot-scale studies to demonstrate the AGC concept. Process and kinetic modeling studies as well as an economic assessment will also be performed. This paper provides an overview of the program and its objectives, and discusses first-year R&D activities including the results of experimental and modeling studies. A bench-scale system has been designed and constructed to meet the high-temperature and high-pressure requirements of the process. Testing is currently in progress to validate the basic principles of AGC. The experimental system design, including the reactor, steam generation, and coal feeding systems will be detailed. In addition, experimental results will be presented and discussed. The results will be used in concert with ongoing kinetic and process modeling efforts to aid in development of a pilot-scale system design for further testing and optimization of the AGC process.

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INTRODUCTION

Projections of increased demands for energy worldwide, coupled with increasing environmental concerns have given rise to the need for new and innovative technologies for energy plants. Incremental improvements in existing plants will likely fall short of meeting future capacity and environmental needs economically. Thus, the implementation of new technologies at large scale is vital. In order to prepare for this inevitable paradigm shift, it is necessary to have viable alternatives that have been proven both theoretically and experimentally at significant scales. The DOE's Vision 21 program aims to support these development needs through funding the development of enabling technologies such as GE EER's advanced gasification-combustion (AGC) process.

GE EER's AGC process features a technology that provides an innovative approach to the use of fossil fuels for energy production. It is expected to meet or exceed environmental goals economically. In addition, it is fuel-flexible, allowing the use of low-cost alternative feedstocks, such as biomass, in addition to coal. The process is also product-flexible, and its operation can be adjusted based on power plant demand to produce various ratios of high-purity hydrogen for a fuel cells and high-temperature/pressure O_2-depleted air for a gas turbine. Inherent to the process is a step that increases H_2 purity by separating CO_2 in the gasification step and releasing it in a sequestration-ready mode.

The current three-year AGC development program integrates lab-scale, bench-scale, and pilot-scale experimental facilities with economic and modeling studies. The objective of this paper is to describe efforts conducted to date on the bench-scale system. A description of the novel AGC technology is provided, detailing AGC chemistry and process dynamics. The design of the bench-scale facility is then detailed, including critical subsystems. Preliminary experimental results are then discussed, followed by a description of planned future work.

TECHNOLOGY DESCRIPTION

The AGC technology makes use of three circulating fluidized bed reactors containing CO_2 sorbent and oxygen transfer material, as shown in Figure 1. Coal and opportunity fuels are partly gasified with steam in the first reactor, producing H_2, CO and CO_2. As CO_2 is absorbed by the CO_2 sorbent, CO is also depleted from the gas phase via the water-gas shift reaction.

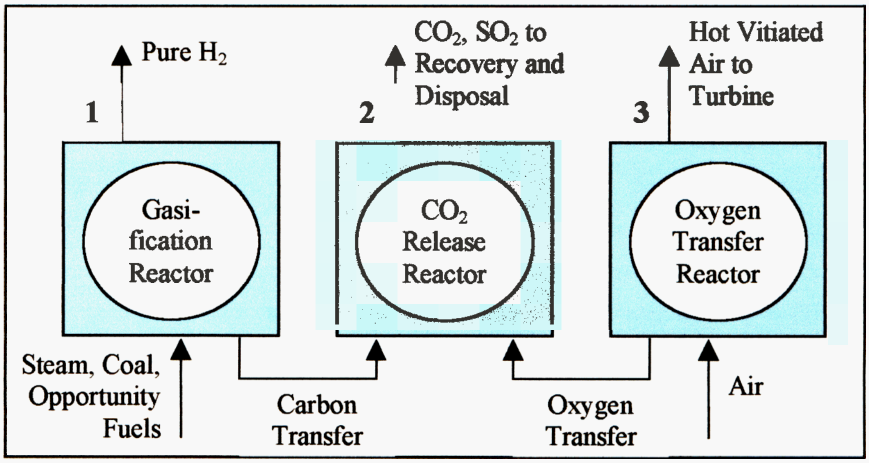

Figure 1. Conceptual design of the AGC technology.

Thus, reactor 1 produces a H_2-rich product stream suitable for use in liquefaction, fuel cells, or turbines.

Gasification is completed in reactor 2, where the oxygen transfer material undergoes a reduction reaction as it provides the oxygen needed to oxidize the remaining carbon. The CO_2 sorbent is regenerated as this increase in temperature forces the release of CO_2 from the sorbent, generating a CO_2-rich product stream suitable for sequestration. Air fed to the third reactor re-oxidizes the oxygen transfer material via a highly exothermic reaction that produces oxygen-depleted air for a gas turbine.

Solids transfer occurs between all three reactors, allowing for the regeneration and recirculation of both the CO_2 sorbent and the oxygen transfer material. Periodically, ash and bed materials will be removed from the system and replaced with fresh bed materials to reduce the amount of ash in the reactor and increase the effectiveness of the bed materials.

BENCH-SCALE SYSTEM DESIGN

The design and assembly of the bench-scale facility have been completed. The reactor, coal injection system, and steam generation system were identified as critical components, and subjected to more rigorous design and verification. The process and instrumentation diagram for the bench-scale system is provided in Figure 2. This diagram shows the reactor at the center,

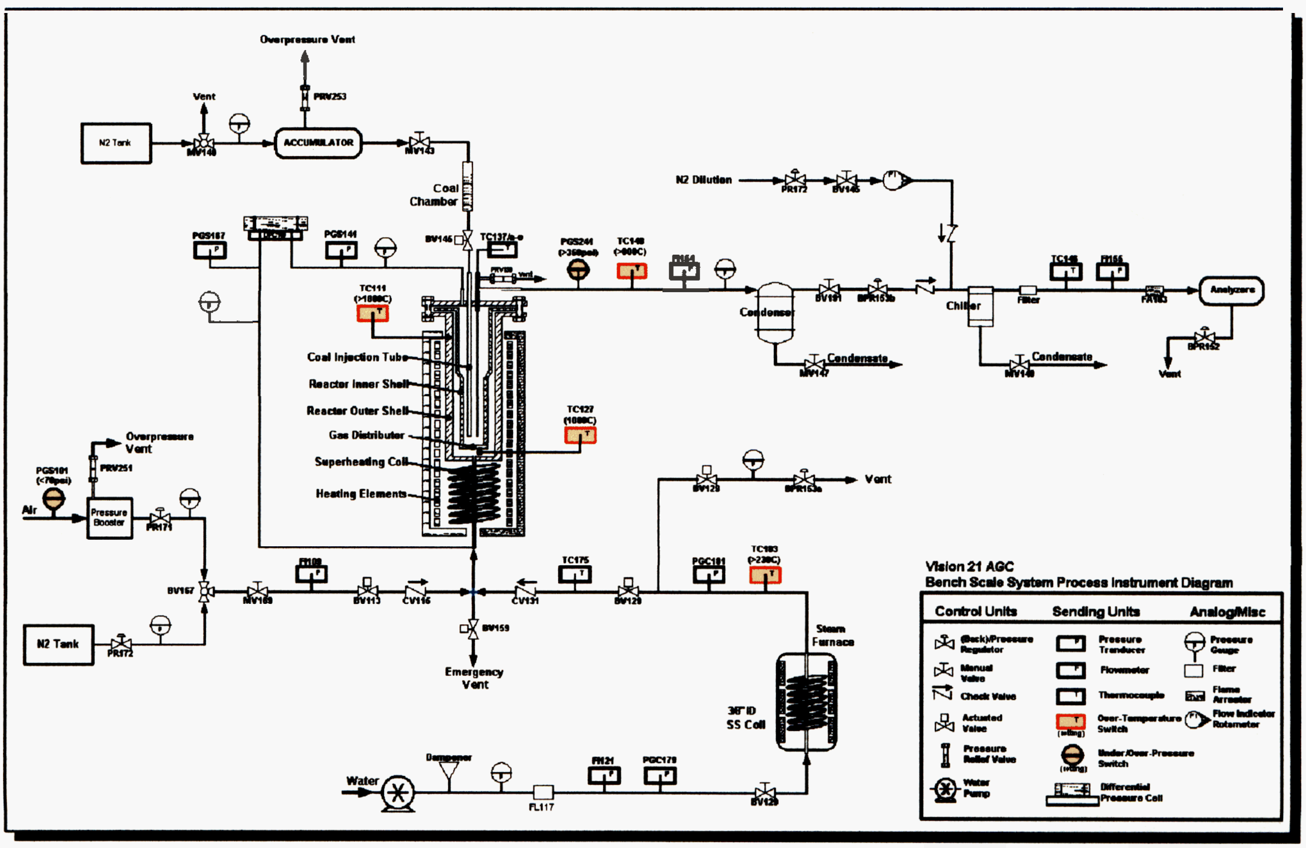

Figure 2. Process and Instrumentation Diagram for the bench-scale experimental system.

with the separate branches for coal, air, and steam feed lines. The product line is also shown, with its condenser for water removal and flowmeters for quantification of the gas produced.

During system design, the need for consistent flow to the analyzers was identified as a concern. Due to the cyclic nature of the bench-scale experiments, it is necessary to add a known flow rate of N_2 to the product gas to ensure consistent flow to the analyzers even when the only flow through the reactor is steam (which is condensed prior to the analyzers). The N_2 feed was added after the backpressure regulator, at a point where the pressure is low. An additional bleed stream of N_2 was later added with the steam at the reactor inlet to ensure the effective operation of the condensers when no product gases are being generated. The flow rate of product gas varies from zero (prior to steam injection) then up to a peak flow rate value (during gasification) and finally down to zero again (after gasification is complete). Although a constant flow rate of N_2 is fed to the system, this cyclic variation in product flow rate results in effective dilution ratios that vary during the course of an experiment. Thus, gas concentrations measured by the CEMS analyzers must be corrected with these varying dilution ratios. This calculation has the potential for introducing error into the data, and is currently being evaluated and validated. For this reason, preliminary experimental results are reported as component flow rates, which are independent of N_2 dilution rate, rather than as measured concentrations.

Reactor Design

The reactor is the heart of the system, and was designed to withstand an environment of 1000°C and 300psi. The reactor is heated by a Lindberg Model 54579-V-s 16kW furnace with a maximum temperature of 1500°C and a 4" inside diameter. Due to the external heating of the reactor, the reactor materials were selected to withstand the full operating temperatures of the process. However, because of gasket temperature limitations, the flanges used to seal the reactor were located outside the hot zone of the furnace.

The reactor (Figure 3) consists of a 4" OD outer shell, and a 2"ID inner shell with an expansion zone. The outer shell is welded to a flange, while the inner shell has a lip that allows it to rest between the outer

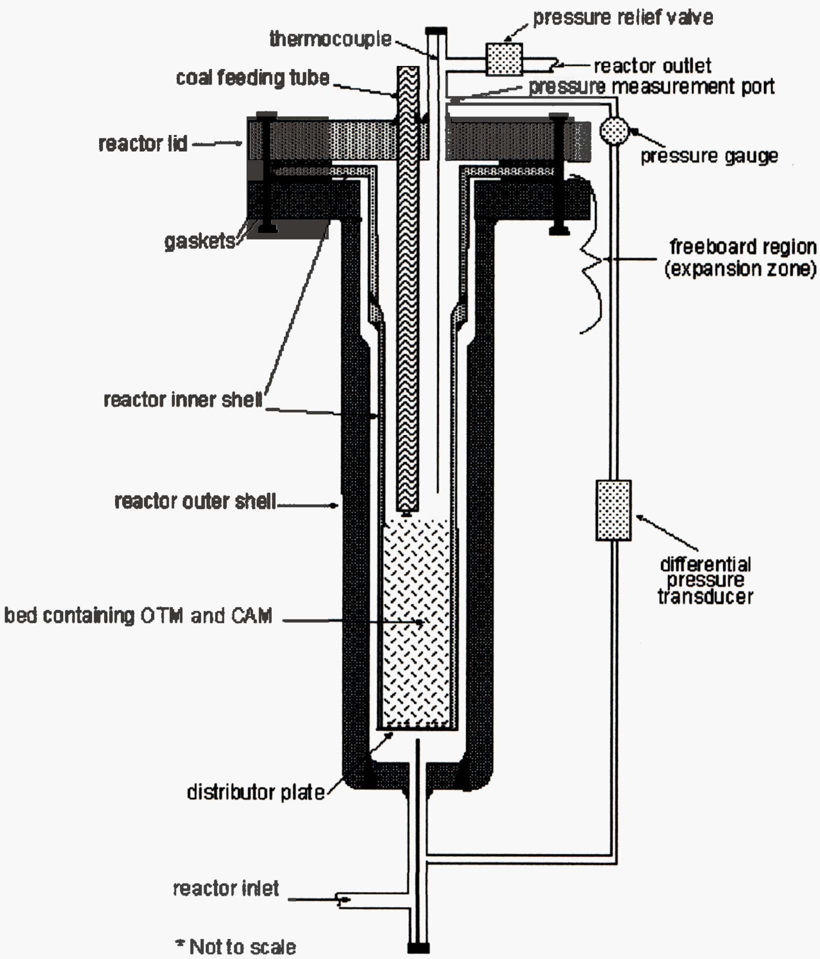

Figure 3. Bench-scale reactor diagram.

shell's bottom flange and the flange lid, with two gaskets used to maintain high-pressure seals.

An Incoloy 800HT alloy was used for the outer shell, selected on the basis of its strength at high temperatures and its ability to withstand the severely oxidizing and severely reducing environments of the process. A detailed stress analysis was conducted to specify the reactor wall thickness. The heat loss through the outer shell walls was estimated in order to specify the reactor length so that the flange at the top of the reactor will not exceed 400°C during operation.

The completed reactor was sent to an independent testing laboratory for certification. The reactor was subjected to conditions of 1000°C and 325psi for over 24 hours with no signs of leakage or permanent deformation. Figure 4 shows the temperature profile across the reactor, with an inset photo of the red-hot reactor taken during the certification test. As shown in the figure, the temperature at the top flange of the reactor did not exceed 400°C.

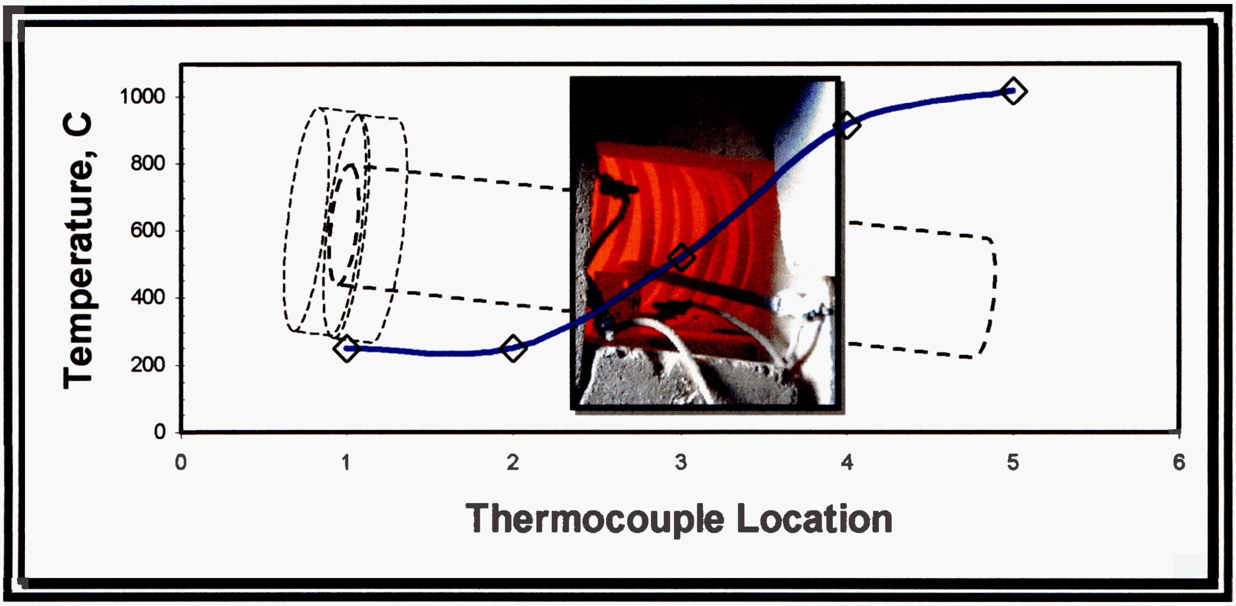

Figure 4. Temperature profile in reactor during certification testing.

Coal Injection

The coal feeding system was designed to inject measured amounts of coal into the high-pressure, high-temperature reactor with minimal plugging, deposits, and coal devolatilization in the feed tube. The coal feeding tube enters the reactor through the flange lid, and extends down into the reactor bed (as shown in the reactor diagram, Figure 3) for enhanced coal mixing with the bed and to prevent coal entrainment. The coal is loaded into a coal reservoir and then an accumulator tank is filled with high-pressure N_2. Once the accumulator is pressurized to a predetermined pressure, the coal reservoir is slowly pressurized. Then the valve between the coal reservoir and the reactor is opened, sending the slug of coal rapidly through the coal delivery tube and into the reactor bed. Shakedown testing of this system was first conducted at ambient temperature and pressure, with differential pressures on the order of 100psi, then testing continued at operating pressures, and finally at high temperature and pressure. The system was modified and optimized as needed to prevent trapping of coal in the upstream portion of the system. This involved streamlining the coal delivery line; eliminating components that led to necking in the flow path. Utilizing heat tape, shakedown testing demonstrated the successful delivery of coal at 550°C. Coal recovery increased with increasing differential pressure, reaching 90% recovery at 100psid. The coal delivery system has subsequently been used for gasification testing at system temperatures and pressures, and the consistency of its operation is being evaluated. Results obtained to date suggest that the coal delivery system operates consistently at the conditions of interest.

Steam Generation

The steam feed system consists primarily of a water pump and a coil located inside an electric steam furnace, as depicted in Figure 5. Instrumentation is provided to measure temperature, pressure, and flow rates at intermediate points of the system in order to evaluate performance. As steam will not be fed to the reactor during start-up, ramping of furnace temperature, etc., a bypass line is used to allow for continuous steam generation while maintaining system pressure. Instrumentation is in place to monitor the temperature and pressure of the steam both before and after the steam preheater coil. Shakedown testing demonstrated the successful generation of steam for water flow rates from 5 – 40 g/min and a furnace temperature of 600 °C. During shakedown testing, an average of one hour was required to reach a steady state of steam production.

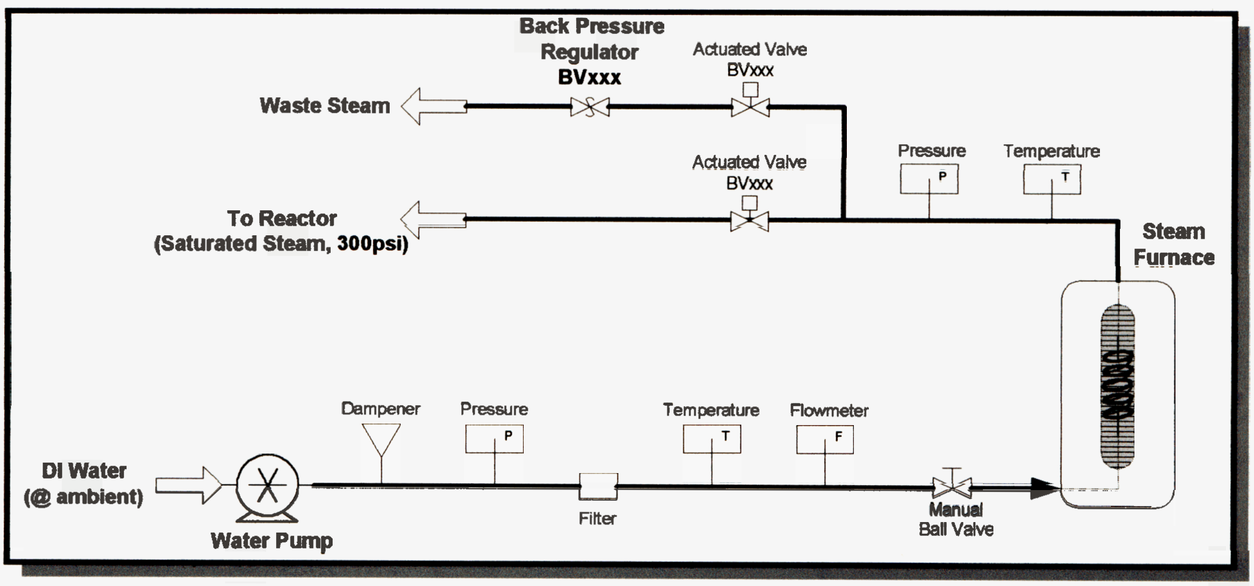

Figure 5. Schematic diagram of steam generator system.

EXPERIMENTAL RESULTS

The objectives of the bench-scale testing task are to collect data on process operation and kinetics under dynamic conditions and aid in developing the modeling tools and the pilot plant equipment design. The bench-scale system is also intended to provide data on individual AGC processes to aid in pilot plant design and testing.

Through preliminary testing, the capabilities of the bench-scale experimental system have been verified, and detailed planning has been conducted to develop a comprehensive approach to testing. Selection of the type and sequence of tests to best provide information about the AGC process for modeling and pilot plant design has been a high priority. The type of information desired from bench-scale testing includes: characterization of coal conversion; quantification of CAM (CO_2 absorber material) and OTM (oxygen transfer material) activity over time; development of global reaction rates for each reactor; characterization of the impact of bed and coal particle size on performance; and parametric testing to identify optimal operating conditions. In addition, data analysis templates have been developed and methodologies for calculation of performance parameters reviewed and validated.

Preliminary experimental testing has focused on fluidization experiments to verify the cold flow modeling results for fluidization flow rates and coal gasification experiments with either an inert bed or a CAM bed. Preliminary data from these tests are discussed below.

Fluidization experiments were performed using an inert bed composed of alumina oxide at 300psi and 850°C. Experimental values of pressure drop were obtained for a range of fluidizing flow rates. Figure 6 illustrates the range of differential pressures measured, and their comparison to theoretical values. The experimental values are in good agreement with the theoretical values, and their scatter can be attributed to experimental variations.

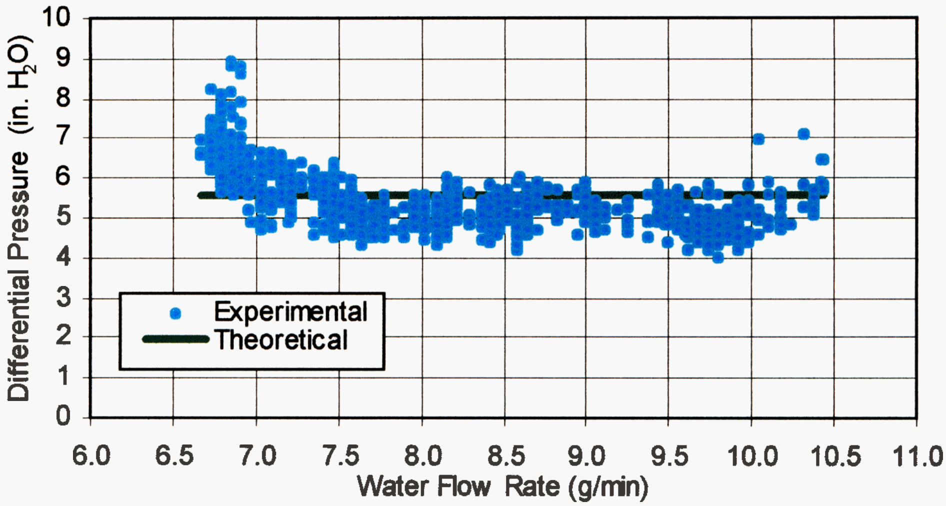

Figure 6. Pressure drop through the reactor bed as a function of fluidization flow rate: a comparison of experimental results with theoretical values.

Coal injection and gasification was conducted with an inert bed to provide a baseline for comparison of CO_2 absorption performance. The coal injection system is currently being scrutinized to identify potential improvements. Minimal fluctuations in reactor temperature and pressure have been observed due to the coal injection transport gas (N_2), with a recovery time of approximately one minute required to restore the initial conditions.

Gasification experiments were also conducted with a bed composed of CO_2-absorbing material (CAM). Coal was injected into the CAM bed and significant CO_2 absorption was observed. Figure 7 shows the difference in CO_2 concentration for gasification experiments conducted in an

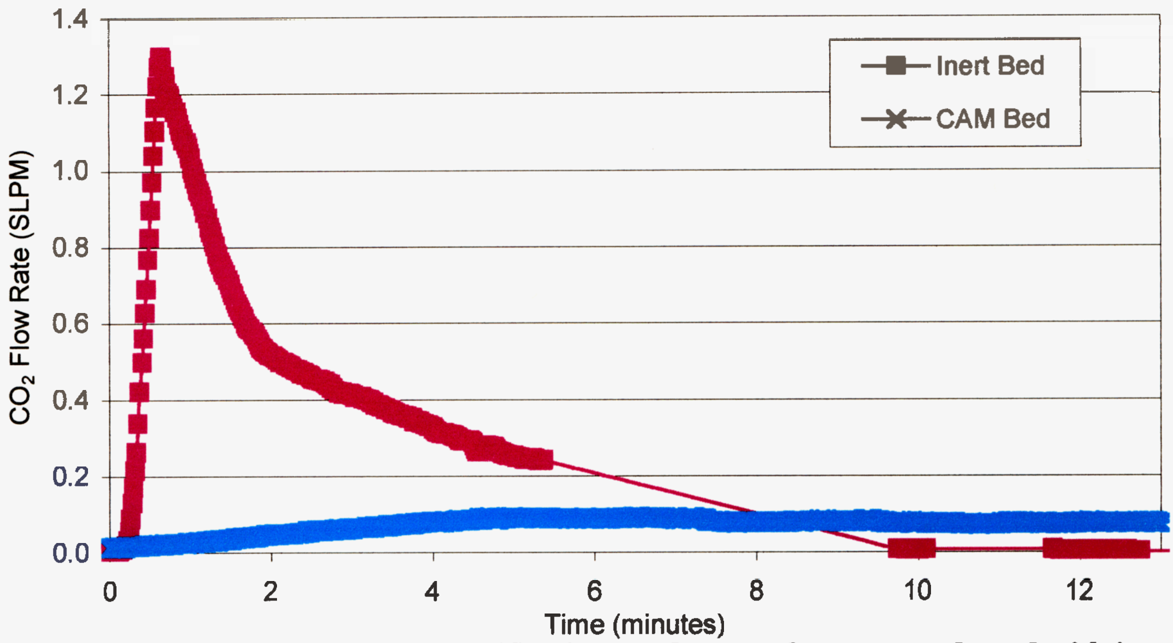

Figure 7. CO_2 concentration in gasification product gas for tests conducted with inert bed and CAM (CO_2-absorbing material) bed.

inert bed and in a CAM bed. The CO_2 concentration increases more rapidly and with a higher peak concentration during gasification in an inert bed.

The CO concentration behaves in a similar manner, with increased concentrations during gasification in an inert bed, as illustrated in Figure 8 for the same test. The reduced CO_2

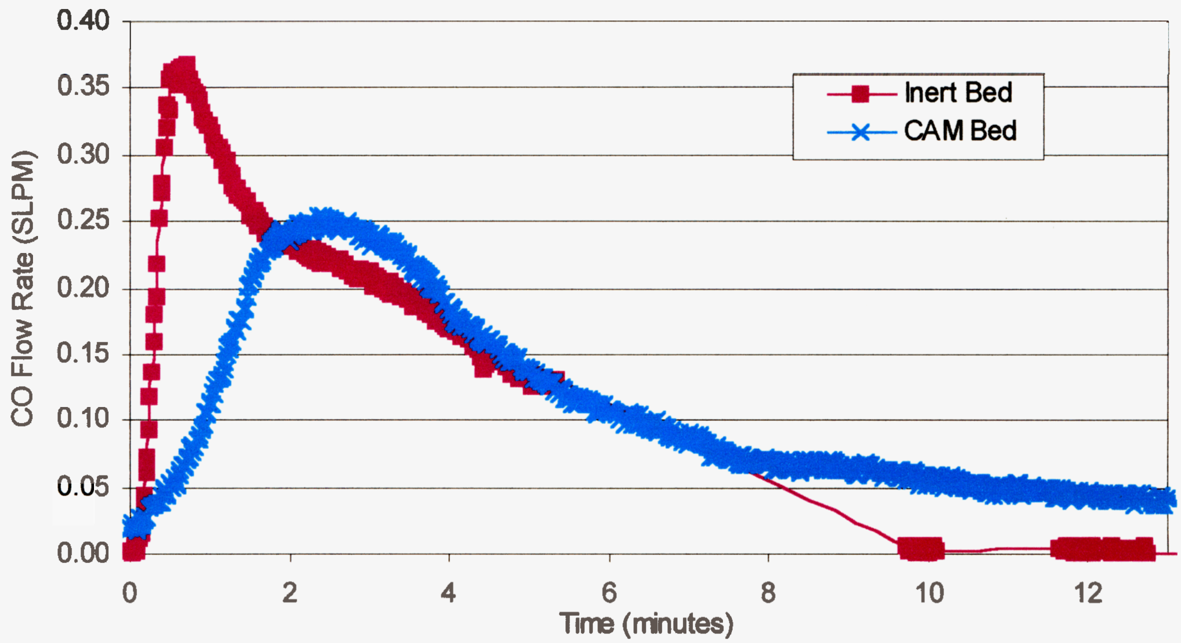

Figure 8. CO concentration in gasification product gas for tests conducted with inert bed and CAM (CO_2-absorbing material) bed.

concentrations are due to the absorption of CO_2 by the CAM bed. Meanwhile, the reduction in CO is caused by the participation of CO in the water-gas shift reaction ($CO + H_2O$ -» $CO_2 + H_2$), driven by the low CO_2 and CO concentrations in the reactor. The product gas flow rates observed during these tests (Figure 9) are consistent with the explanations provided, as the decreased CO_2 concentrations also result in lower product gas flow rates. A unique feature of the AGC process is its inherent production of high-purity H_2 due to the absorption of CO_2 and related reduction in CO concentration. Testing conducted to date has focused on measurements of the CO_2 and CO, although direct measurements of H_2 concentration will be conducted with a GC analyzer in the near future.

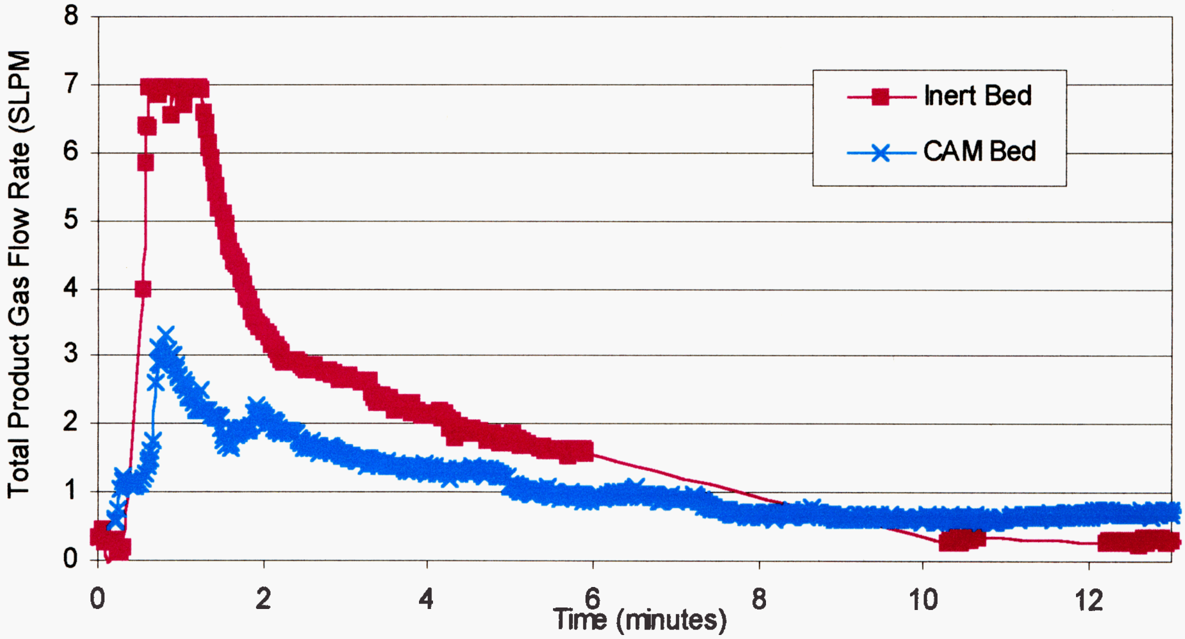

Figure 9. Product gas flow rate during gasification for tests conducted with inert bed and CAM (CO_2-absorbing material) bed.

The reproducibility of the tests is also continuously being evaluated. Figure 10 shows the CO_2 flow rates from three different gasification tests conducted with CAM beds. The general trends are similar, although Run B shows higher concentrations than Runs A and C.

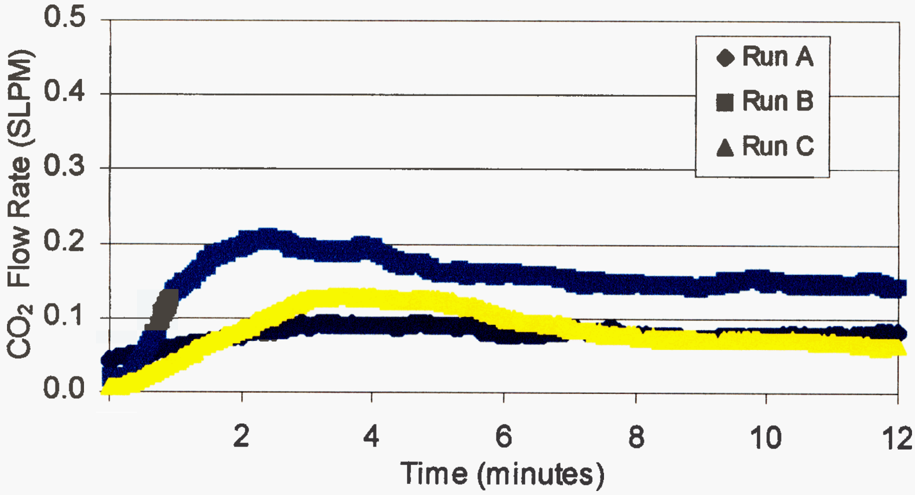

Figure 10. CO_2 measurements during coal gasification with a CAM (CO_2-absorbing material) bed for three different test runs.

However, Runs A and C were each conducted with fresh CAM beds, and run B was conducted with a regenerated bed after Run A. Thus, differences in CO_2 concentrations may be due to incomplete regeneration of the CAM bed, which is currently being investigated experimentally.

These preliminary results are currently under review and detailed calculations are being used to verify the mass balance around the system and evaluate the reproducibility of the results, as well as the reliability of the system.

FUTURE WORK

Future work will focus on testing and analysis of results from both the lab-scale and bench-scale systems. This information will be used in ongoing pilot-scale design efforts. In addition, continuing modeling efforts will provide a more clear understanding of the kinetics and fluidization processes. Other studies will aid in ensuring that the technology is developed in such a way that it meets market needs, both through its economic viability as well as through its use of opportunity fuels.

Bench-scale testing activities will focus on parametric testing to identify optimized operating conditions and specific tests to characterize material performance. Results of these tests will be used along with lab-scale results to modify and validate kinetic and process models, as well as provide inputs for economic evaluation efforts.

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